

## Nonstandard Central Engines in Nearby Galaxies

Luis C. Ho

*The Observatories of the Carnegie Institution of Washington, 813 Santa Barbara St., Pasadena, CA 91101, U.S.A.*

**Abstract.** We argue that nearby galaxy nuclei contain massive black holes that are fueled by low radiative efficiency accretion flows.

### 1. Nuclear Activity in Nearby Galaxies

A significant fraction of local galaxies exhibit signs of nuclear activity in the form of emission-line nuclei classified as Seyferts or LINERs. According to the Palomar spectroscopic survey of nearby galaxies, 43% of all northern galaxies brighter than  $B_T = 12.5$  mag are active (Ho, Filippenko, & Sargent 1997), albeit at a level substantially weaker than traditionally studied AGNs such as classical Seyfert nuclei and quasars. The sheer abundance of low-luminosity AGNs (LLAGNs), especially LINERs which make up two-thirds of the population, compels us to give them proper attention when considering AGN issues of a statistical nature.

We do not yet have a full understanding of the physical origin of LINERs. Particularly thorny are the narrow-line objects (type 2 LINERs and transition objects), where in some cases the AGN signature can be either ambiguous or absent (Ho 2001a; Barth 2001). On the other hand, the affiliation of type 1 objects (those with detectable broad emission lines) with nonstellar processes seems quite secure. This contribution highlights some of the salient features of type 1 LLAGNs and implications we might draw concerning the nature of their central engines.

### 2. Notable Characteristics of Low-luminosity AGNs

We begin by listing some of the observational properties that are unique to LLAGNs. When observing these sources, it should be noted that one must exercise caution to obtain *nuclear* fluxes — the quantities most pertinent to the AGN and most analogous to observations of quasars. In general the central source is sufficiently weak that it is completely overwhelmed by emission from the host galaxy. This applies to virtually all wavelengths. In order to reliably quantify the nuclear fluxes, one needs observations with good sensitivity, and more crucially, high angular resolution (generally  $\lesssim 1''$ ).

(1) *Accretion luminosities and Eddington ratios.* LLAGNs are not only intrinsically faint, but more importantly, their accretion luminosities are low relative to their Eddington luminosities. Ho (2002) used the nuclear X-ray luminosities of a large sample of nearby galaxies to estimate their nuclear bolometric luminosities. Figure 1a shows that  $L_{\text{bol}}$  is generally higher in Seyferts

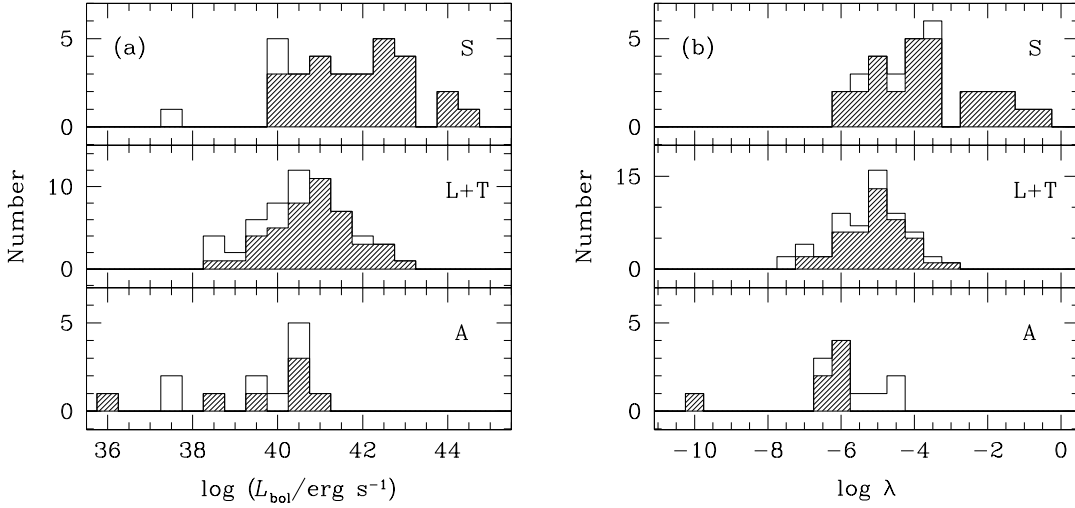


Fig. 1. Distribution of (a) nuclear bolometric luminosities and (b) Eddington ratios  $\lambda \equiv L_{\text{bol}}/L_{\text{Edd}}$  for Seyferts (S), LINERs and transition objects (L+T), and absorption-line nuclei (A). Open histograms denote upper limits. Adapted from Ho (2002).

than in LINERs, which themselves are more luminous than absorption-line nuclei (objects with no nuclear optical emission lines). Using the empirical relationship between black hole mass and bulge stellar velocity dispersion (Gebhardt et al. 2000; Ferrarese & Merritt 2000), one can obtain  $L_{\text{Edd}}$ , and hence  $\lambda$ , which is a function of  $\dot{M}/\dot{M}_{\text{Edd}}$ . Although the overlap is considerable,  $\lambda$  decreases systematically from Seyferts to LINERs to absorption-line nuclei (Fig. 1b). Note, in particular, that *all* LINERs are characterized by  $\lambda \lesssim 10^{-3}$  and most have  $\lambda \lesssim 10^{-4}$ . (It should be remarked that not all LLAGNs necessarily have low  $\lambda$ . A good example is NGC 4395, one of the lowest luminosity AGNs known; it has  $\lambda \gtrsim 2 \times 10^{-3}$  according to Moran et al. 1999.)

(2) *Spectral energy distributions (SEDs)*. With few exceptions, the SEDs of LLAGNs lack the optical–UV “big blue bump,” a feature conspicuous in unobscured high-luminosity AGNs that is attributed to thermal emission from an optically thick, geometrically thin accretion disk. This unusual property was first quantified systematically by Ho (1999), and Ho et al. (2000) noted that it is also present in AGNs with double-peaked broad emission lines. Figure 2 shows the full SEDs of the objects discussed by Ho et al. (2000), updated with NGC 4579, which Barth et al. (2001) recently discovered to belong to the same class. Another attribute of these SEDs is that they are generically “radio loud,” defined here by the convention that the radio-to-optical luminosity ratio  $R$  exceeds a value of 10. In fact, radio loudness seems to be a property common to essentially *all* nearby weakly active nuclei (Ho 2001b) and a substantial fraction of Seyfert nuclei (Ho & Peng 2001). Moreover, the degree of radio loudness evidently changes systematically with accretion rate;  $R$  increases with decreasing  $\lambda \equiv L_{\text{bol}}/L_{\text{Edd}}$  (Fig. 3).

(3) *Structure of accretion disk*. The above-mentioned peculiar SEDs of LLAGNs cannot be readily accommodated by the predicted spectra of canonical optically

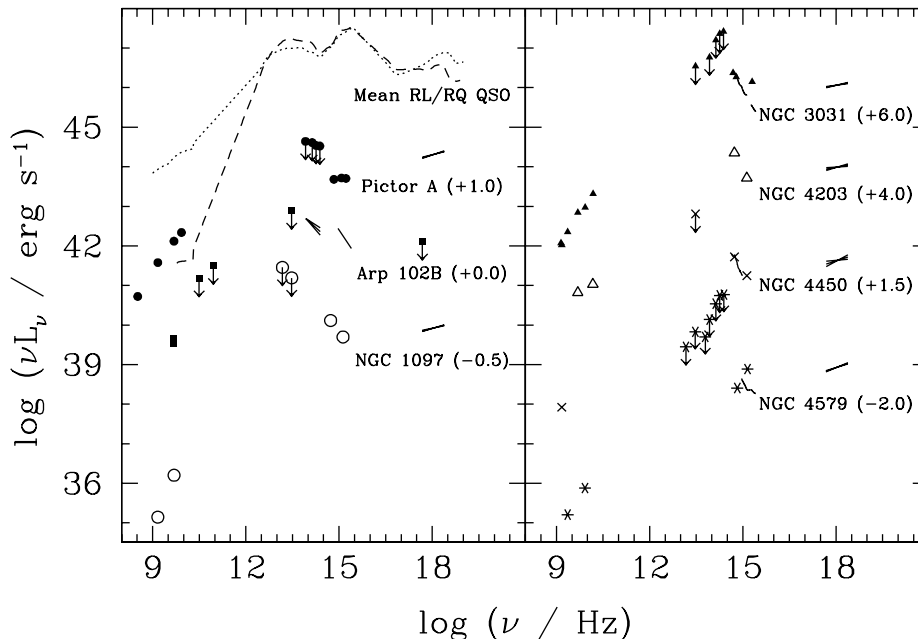


Fig. 2. Nuclear SEDs of objects with double-peaked broad emission lines. Adapted from Ho et al. (2002).

thick, geometrically thin accretion disks. The few cases that have been modeled in detail need to invoke a central structure consisting of a quasi-spherical, optically thin advection-dominated accretion flow (ADAF; see reviews by Narayan, Quataert, & Mahadevan 1998 and Quataert 2001), a concept similar to what Rees et al. (1982) called an “ion-supported torus.” ADAFs are thought to arise when the mass accretion rate drops below a critical threshold of  $\dot{M} \approx 10^{-2} \dot{M}_{\text{Edd}}$ . In addition to a puffed-up inner hot corona, the SED fits of some objects (Lasota et al. 1996; Quataert et al. 1999; Lu & Wang 2000) require a component from an outer thin disk. The inner edge of the truncated disk, or the transition radius between the inner ADAF and outer thin disk, lies at  $r \approx \text{few} \times (10 - 100) R_S$ ,  $R_S$  being the Schwarzschild radius.

(4) *Double-peaked broad emission lines.* The ADAF + truncated disk cartoon for the central structure (see Fig. 4) is further implicated from the recent frequent detection of double-peaked broad emission lines in nearby LLAGNs (Ho et al. 2000, and references therein).

(5) *X-ray Fe K $\alpha$  line.* The X-ray spectra of LLAGNs generally require a hard power-law component with photon indices  $\Gamma \approx 1.7 - 1.9$ , but the relativistically broadened Fe K $\alpha$  line at 6.4 keV is either extremely weak or absent (Terashima et al. 2001). The Fe K is thought to arise from fluorescence off of cold material near the center that subtends a large solid angle, commonly interpreted to be the standard thin accretion disk. The absence of this feature in LLAGNs is consistent with the accretion-disk structure suggested by (3) and (4) above.

(6) *Low-ionization state.* As mentioned in § 1, the majority of nearby LLAGNs are classified as LINERs, objects with lower ionization state than Seyferts. It is notable that radio galaxies with double-peaked broad lines (e.g., Arp 102B,

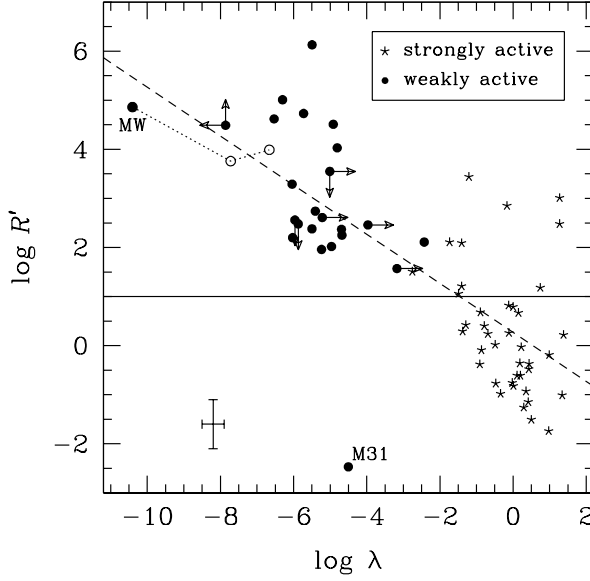


Fig. 3. Distribution of the nuclear radio-to-optical luminosity ratio  $R'$  vs.  $\lambda \equiv L_{\text{bol}}/L_{\text{Edd}}$ . The *solid line* marks the formal division between radio-loud and radio-quiet objects,  $R' = 10$ . The *dashed line* is the best-fitting linear regression line. Adapted from Ho (2001b).

3C 390.3, Pictor A) also typically have LINER-like narrow-line ratios (e.g., Eracleous & Halpern 1994).

### 3. A Unifying Physical Picture

We propose that the above set of characteristics of LLAGNs can be accommodated within the theoretical framework of an ADAF, or some closely related variant thereof (Narayan et al. 1998; Quataert 2001). The picture we envision is depicted in Figure 4: a hot, ion-supported torus or ADAF exists within some transition radius, exterior to which it illuminates a thin disk. ADAFs have radiative efficiencies much less than the canonical 10% for thin disks because they cannot cool effectively, and so they naturally produce low luminosities. Consistent with the models, the observed Eddington luminosity ratios of LINERs invariably lie below the critical threshold of  $\lambda \lesssim 10^{-2}$ . Several emission mechanisms (cyclo-synchrotron, inverse Compton scattering, and bremsstrahlung) give rise to the broad-band spectrum from radio to X-ray energies. With an absent or truncated thin disk, however, the accretion structure generates little or no emission from the traditional optical-UV big blue bump. Emission in this band instead comes from inverse Compton scattering of cyclo-synchrotron photons, and its strength increases sensitively with rising  $\dot{M}/\dot{M}_{\text{Edd}}$  (see e.g., Fig. 1 of Mahadevan 1997). The radio component, on the other hand, is persistently prominent because cyclo-synchrotron emission contributes significantly to the cooling budget of an ADAF. Both of these features qualitatively account for the peculiar shape of the SEDs, their generic “radio loudness,” and the inverse correlation between  $R$  and  $\lambda$  (Fig. 3). In detail, the steeply falling NIR-UV spectrum ( $f_\nu \propto \nu^{-\alpha}$ ,  $\alpha = 1.5 - 2.5$ ) observed in many objects (Ho 1999; Fig. 2) suggests an extra component in addition to an ADAF. This emission plausibly comes from an outer thin disk. With an inner radius located at  $r \approx \text{few} \times (10 - 100)R_S$ , the disk is relatively cool: the big blue bump shifts to a “big red bump,” and the NIR-UV tail is equivalent to the soft X-ray excess component

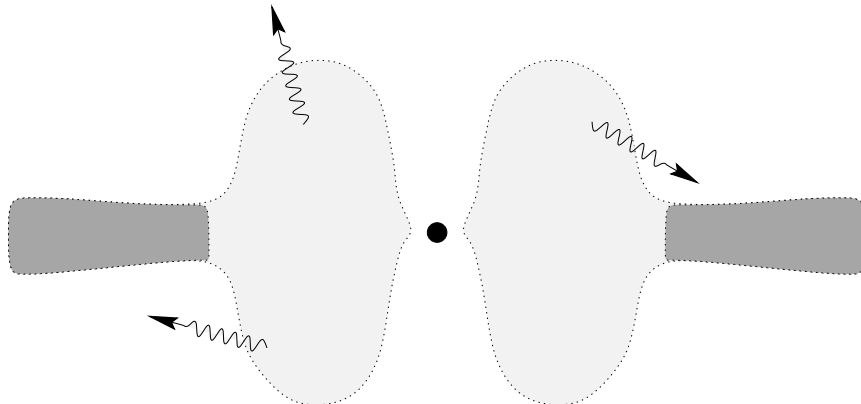


Fig. 4. A cartoon depicting the structure of the accretion flow surrounding weakly active massive black holes. An inner ADAF (ion-supported torus) irradiates an outer thin disk. Taken from Shields et al. (2001).

of high-luminosity AGNs. This very same outer disk has been invoked to produce the double-peaked broad Balmer lines (e.g., Chen, Halpern, & Filippenko 1989). The outer thin disk, even when present, subtends too small a solid angle with respect to the primary X-rays from the ADAF to generate strong Fe K $\alpha$  emission.

Lastly, we note that low-ionization spectra may emerge quite naturally in the scenario suggested here. In the context of AGN photoionization models, it is well known that LINER-like spectra can be produced largely by lowering the “ionization parameter”  $U$ , typically by factors of 10–100 below those in Seyferts (e.g., Halpern & Steiner 1983; Ferland & Netzer 1983; Ho, Filippenko, & Sargent 1993). Figure 1a shows that the nuclear luminosities of LINERs indeed are at least a factor of 10 lower than in Seyferts. In fact, the weakness of the UV emission in the SEDs of LINERs suggests that the ionizing luminosity should be reduced by an even larger factor. Two other effects may be important in boosting the low-ionization lines. All else being equal, hardening the ionizing spectrum (by removing the big blue bump) in photoionization calculations creates a deeper partially ionized zone from which low-ionization transitions, especially [O I]  $\lambda\lambda 6300, 6363$ , are created. Because of the prominence of the radio spectrum, cosmic-ray heating of the line-emitting gas by the mildly relativistic electrons in the ADAF may be nonnegligible; one effect of this process is again to enhance the low-ionization lines (Ferland & Mushotzky 1984).

**Acknowledgments.** L.C.H. acknowledges financial support through NASA grants from the Space Telescope Science Institute (operated by AURA, Inc., under NASA contract NAS5-26555).

## References

- Barth, A. J. 2001, in *Issues in Unification of AGNs*, ed. R. Maiolino, A. Marconi, & N. Nagar (San Francisco: ASP), in press

- Barth, A. J., Ho, L. C., Filippenko, A. V., Rix, H.-W., & Sargent, W. L. W. 2001, *ApJ*, 546, 205
- Chen, K., Halpern, J. P., & Filippenko, A. V. 1989, *ApJ*, 339, 742
- Eracleous, M., & Halpern, J. P. 1994, *ApJS*, 90, 1
- Ferland, G. J., & Mushotzky, R. F. 1984, *ApJ*, 286, 42
- Ferland, G. J., & Netzer, H. 1983, *ApJ*, 264, 105
- Ferrarese, L., & Merritt, D. 2000, *ApJ*, 539, L9
- Gebhardt, K., et al. 2000, *ApJ*, 539, L13
- Halpern, J. P., & Steiner, J. E. 1983, *ApJ*, 269, L37
- Ho, L. C. 1999, *ApJ*, 516, 672
- . 2001a, in *IAU Colloq. 184, AGN Surveys*, ed. R. F. Green, E. Ye. Khachikian, & D. B. Sanders (San Francisco: ASP), in press
- . 2001b, *ApJ*, in press
- . 2002, in preparation
- Ho, L. C., et al. 2001, *ApJ*, 549, L51
- . 2002, in preparation
- Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1993, *ApJ*, 417, 63
- . 1997, *ApJ*, 487, 568
- Ho, L. C., & Peng, C. Y. 2001, *ApJ*, 555, 650
- Ho, L. C., Rudnick, G., Rix, H.-W., Shields, J. C., McIntosh, D. H., Filippenko, A. V., Sargent, W. L. W., & Eracleous, M. 2000, *ApJ*, 541, 120
- Lasota, J.-P., Abramowicz, M. A., Chen, X., Krolik, J., Narayan, R., & Yi, I. 1996, *ApJ*, 462, 142
- Lu, Y., & Wang, T. 2000, *ApJ*, 537, L103
- Mahadevan, R. 1997, *ApJ*, 477, 585
- Moran, E. C., Filippenko, A. V., Ho, L. C., Shields, J. C., Belloni, T., Comastri, A., Snowden, S. L., & Sramek, R. A. 1999, *PASP*, 111, 801
- Narayan, R., Mahadevan, R., & Quataert, E. 1998, in *The Theory of Black Hole Accretion Discs*, ed. M. A. Abramowicz, G. Björnsson, & J. E. Pringle (Cambridge: Cambridge Univ. Press), 148
- Quataert, E. 2001, in *Probing the Physics of Active Galactic Nuclei by Multiwavelength Monitoring*, ed. B. M. Peterson, R. S. Polidan, & R. W. Pogge (San Francisco: ASP), 71
- Quataert, E., Di Matteo, T., Narayan, R., & Ho, L. C. 1999, *ApJ*, 525, L89
- Rees, M. J., Begelman, M. C., Blandford, R. D., & Phinney, E. S. 1982, *Nature*, 295, 17
- Shields, J. C., et al. 2001, in *Probing the Physics of Active Galactic Nuclei by Multiwavelength Monitoring*, ed. B. M. Peterson, R. S. Polidan, & R. W. Pogge (San Francisco: ASP), 327
- Terashima, Y., Iyomoto, N., Ho, L. C., & Ptak, A. F. 2001, *ApJS*, in press